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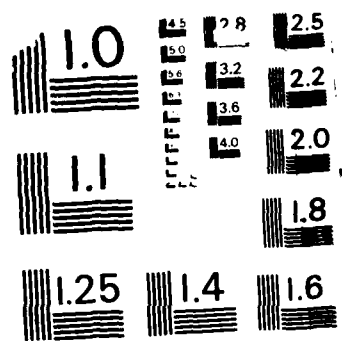
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FINAL TECHNICAL REPORT

on

STUDIES OF MILLIMETER-WAVE
DIFFRACTION DEVICES
AND MATERIALS

Phase III

Prepared For:
Air Force Office of Scientific Research
Bolling Air Force Base, D.C. 20332

August 31, 1986

by

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<p>A millimeter-wave beam steerable antenna, using "diffraction electronics", was explored at 94 GHz operating frequency.</p> <p>This report documents the third year of the research. During this year the effort was largely centered on semiconductor periodic structures in the attempt to find high-speed switching and steering rates. Photoconductive structures, using CdS or GaAs layers driven by laser illumination, showed inadequate light-to-dark conductivity ratios to create a radiating periodic structure.</p> <p>An alternate structure, formed by a CdS layer on the faceplate of a cathode ray tube, was then examined. This layer was evanescently coupled through a thin polystyrene layer ($\epsilon_r = 2.5$) to a quartz waveguide ($\epsilon_r = 3.8$). By "writing" conducting lines on the semi-insulating CdS with an electron beam, a periodic structure was obtained. Radiation efficiency was about 4 percent.</p>					
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PREFACE

This research was supported by the Air Force Office of Scientific Research, Bolling AFB, D.C., 20332, under Contract No. F49620-85-C-0068. Captain Kevin Malloy served as the AFOSR program manager.

STUDIES OF MILLIMETER-WAVE DIFFRACTION DEVICES AND MATERIALS

by

Eugene R. Leach, Milton R. Seiler,
and Jennifer I. Halman

1.0 INTRODUCTION

This is the final technical report on "Millimeter-Wave Diffraction Devices and Materials" prepared under Contract No. F49620-85-C-0068 for the Air Force Office of Scientific Research. The period covered is April 1985 through August 1986.

This study is a continuation of earlier work ~~under Contract No. F49620-82-C-0099~~ wherein Battelle examined a variety of "diffraction electronics" effects. The concept involved is one where a dielectric waveguide interacts with a nearby periodic structure or grating through evanescent mode coupling. By changing the period of the nearby structure, a beam steerable antenna is achieved. The earlier work revealed mechanical, fluidic, and laser-photoconductor ways of achieving a grating containing alternating regions of high- and low-electrical conductivity. (1,2)*

The center frequency for the past and current work was 94 GHz. This region of the spectrum was selected because discrete phase shifter technology is not sufficiently advanced to permit conventional phased array assembly at this frequency. The diffraction electronics concept offered the potential by-pass of the need for phase shifters, and hence it was necessary to explore the concept for ways to achieve rapid beam steering.

During the past year, under Phase III of the program, the work largely examined semiconductor gratings. The intent was to find higher switching speeds and beam steering rates than had been revealed in the earlier, preliminary work.

The following sections of this report provide a summary of results, the research objectives, and a description of experimental devices and materials. Personnel associated with the research and references are listed at the end of the report.

*References are listed on page 20.

2.0 SUMMARY

The study reported herein involved the subject of implementing millimeter-wave beam steerable antennas using a technique known as "diffraction electronics". In this approach to beam steering, an alternating high- and low-conductivity structure is placed in proximity to a dielectric waveguide. The interaction between waveguide and periodic structure, by evanescent mode coupling, modifies the boundary conditions on the waveguide. A directive antenna pattern for reception or transmission is formed in a direction dictated by the period of the structure. By constructing variable period structures, a beam steerable antenna may be achieved.

This report documents the third year of the research. During this year the effort was largely centered on semiconductor periodic structures in the attempt to find high-speed switching and steering rates.

Photoconductive structures, using CdS or GaAs layers driven by laser illumination, showed inadequate light-to-dark conductivity ratios to create a radiating periodic structure. Laser diodes were the source of illumination rather than the previously reported Nd:YAG illumination experiments.⁽¹⁾ The negative results show that excessively high illumination is necessary to achieve useful antennas. This result means that practical photoconductive antennas do not appear feasible.

An alternative structure, formed by a CdS layer on the faceplate of a cathode ray tube, was then examined. This layer was evanescently coupled through a thin polystyrene layer ($\epsilon_r = 2.56$) to a quartz waveguide ($\epsilon_r = 3.8$). By "writing" conducting lines on the semi-insulating CdS with an electron beam, a periodic structure was obtained. Radiation efficiency was about 4 percent. Measurements and further optimization were never totally completed because of repeated electrical failure of the CRT high-voltage and/or filament circuits.

The authors conclude that the CRT method offers promise for high-speed beam steering (about 300 beam position changes per second). Optimization of the semi-insulating layer material, thickness, resistivity, and distance from the waveguide would be necessary. The CRT tube failure, according to the tube manufacturer, could be solved by coatings to eliminate trace Cd contamination on the cathode and filament.

3.0 RESEARCH OBJECTIVES

Examine silicon and gallium arsenide semiconducting films for their photoconductive properties relevant to diffraction electronics. Studies will include both amorphous and epitaxial layers with varying electronic properties.

Study the design and waveguides to determine structures compatible with both diffraction antenna and millimeter-wave integrated circuits.

4.0 RESEARCH RESULTS

4.1 Background

The diffraction electronics beam steering concept depends upon the creation of controlled periodic structures in proximity to a dielectric waveguide.⁽²⁾ Figure 1 shows the concept. The beam steering angle, θ , is given by

$$\cos \theta = \frac{c}{vg} + m \frac{\lambda}{\mathcal{L}}$$

where

c = speed of light in vacuum, m/sec

vg = speed of propagation in the waveguide m/sec

m = mode of operation (normally $m = -1$)

λ = free-space wavelength, m

\mathcal{L} = period of the structure, m.

By creating structures where the period, \mathcal{L} , may be changed electronically or mechanically, a beam steerable antenna is achieved.

The efforts reported herein were devoted to semiconductor layers that could be modulated by an electron beam or by laser illumination.

Previous work⁽¹⁾ has shown that two criteria must be met:

- The high-to-low electrical conductivity ratio should be on the order of 1000 or more
- The high conductivity region should be at least 1 mho/cm or more.

The above constraints are severe for photoconductors. Generally high light-to-dark conductivity ratios can be achieved in photoconductive CdS, but this ratio may not be obtainable simultaneously with 1 mho/cm conductivity. GaAs photoconductors appear not to offer any advantages over CdS.

The photoconductive experiments produced negative results and are documented in the Appendix of this report. Some partial success was obtained with cathode-ray-tube bombardment of CdS layers, however, and these results are documented in the following paragraphs.

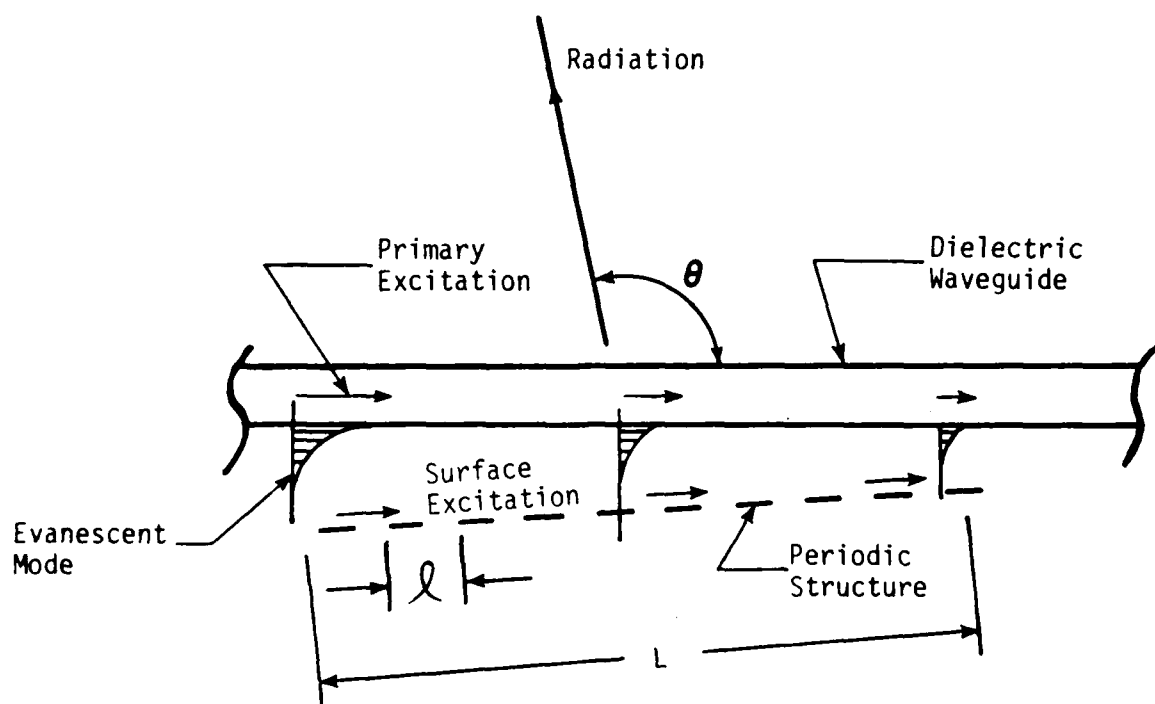


FIGURE 1. DIFFRACTION ELECTRONICS GEOMETRY.

4.2 Cathode-Ray-Tube Diffraction Antenna

The overall arrangement of the experimental device is shown in Figure 2. The concept involves a quartz waveguide with a relative dielectric constant of 3.8 (See Reference 3). This medium was selected so that the nearby polystyrene of the faceplate ($\epsilon_r \approx 2.56$) would possess a lower dielectric constant. The wave will tend to stay in the higher permittivity region--producing the desired propagating mode. A CdS layer, approximately 0.025 cm thick, was applied to the underside of the polystyrene faceplate at a distance of 1.5 mm to 0.5 mm from the quartz waveguide. This thin polystyrene layer must sustain the vacuum of the CRT.

Figure 3 shows the basic CRT, a Tektronix No. 154-0629-01 used in a hard copy printer No. 4361. Figure 4 shows the same CRT with the faceplate removed by diamond saw. Figure 5 shows the new mounted faceplate with hollow metallic WR-10 waveguide. The oval region in the center is the region containing the CdS layer. Figure 6 is a close-up view of the faceplate with all components, WR-10 and quartz waveguide, installed.

The entire assembly was evacuated to about 10^{-7} Torr prior to tube operation. Some outgassing of the CdS layer was evident upon initial bombardment with the electron beam. This outgassing is believed to be the source of contamination of the cathode and filament that led to frequent tube failure.

4.2.1 CdS Layer Preparation

The CdS layers were prepared in a fashion similar to the photoconductive layers--see Appendix. The experience gained on the current program with this photoconductive material allowed reproducible, easily applied, layers of semi-insulating material.

Starting Materials

1. CdCl_2 (2-1/2 H_2O) (Cadmium Chloride Hydrate)
 - Vendor: J. T. Baker
 - Particle Size: 325 mesh
 - Purity: 99.98 percent
 - Molecular Weight: 228.35
 - Density: 4.05
 - Melting Point: 568 C

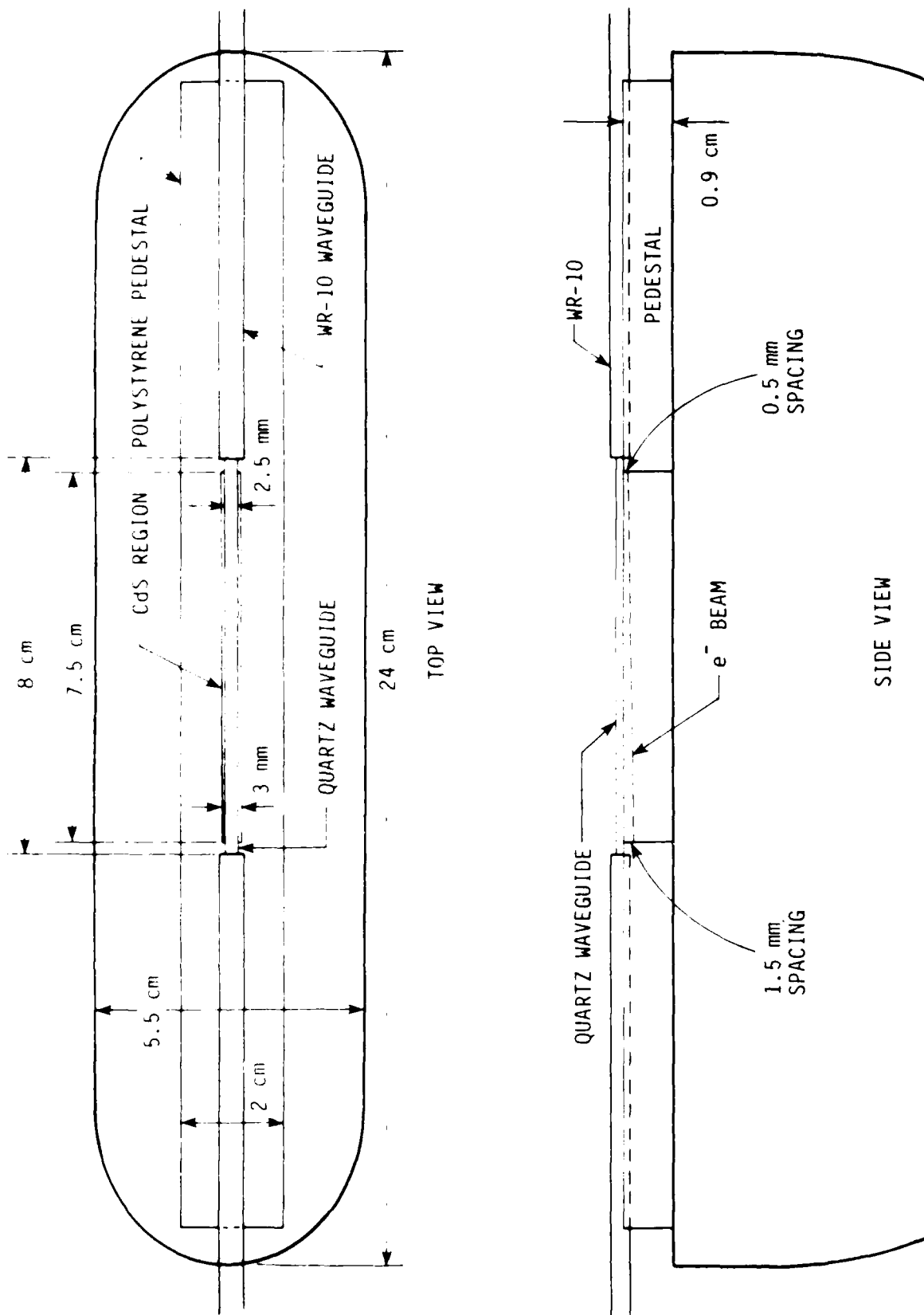


FIGURE 2. CRT - DRIVEN DIFFRACTION ANTENNA.

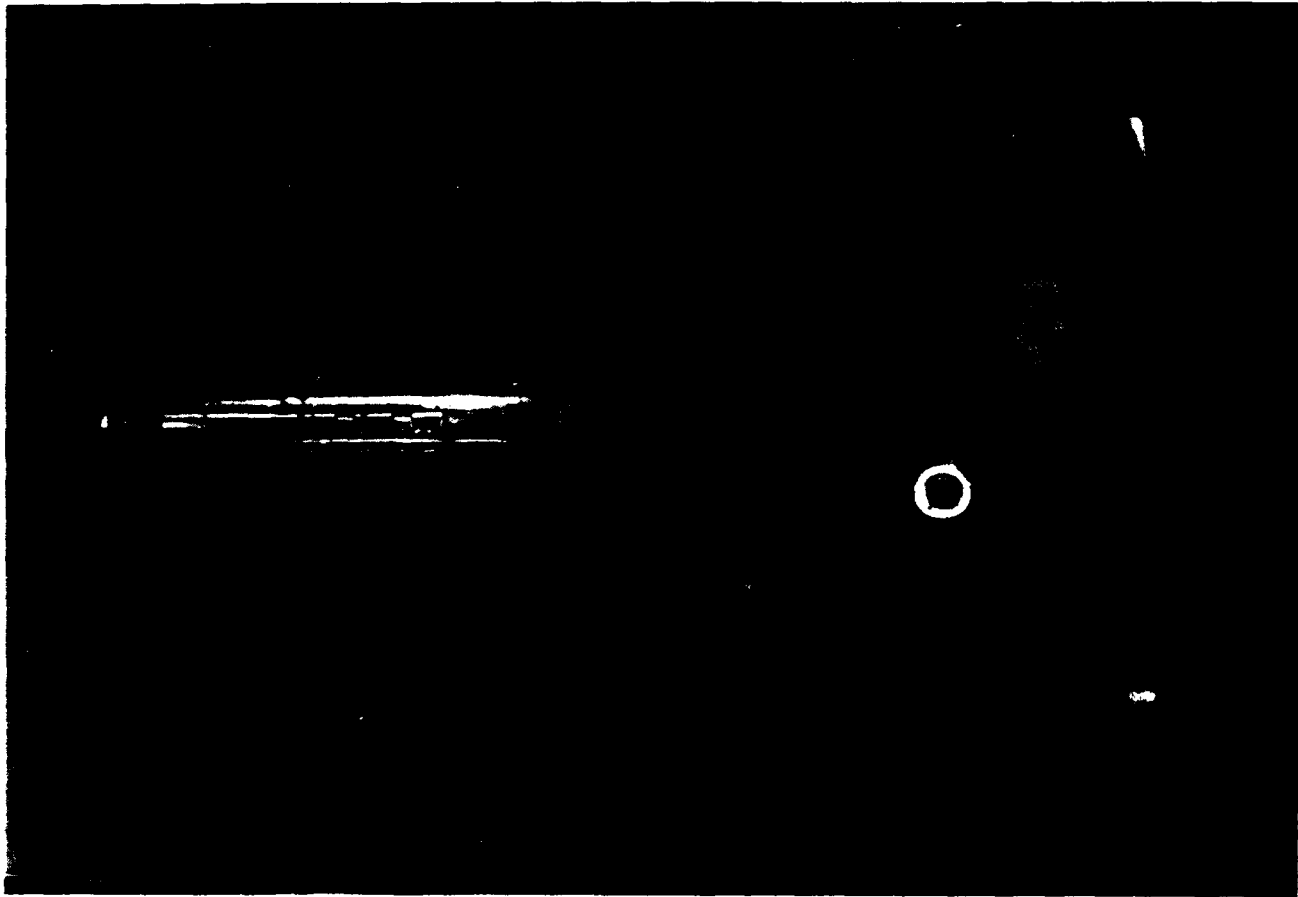


FIGURE 3. BASIC CRT.



FIGURE 4. CRT WITH FACEPLATE REMOVED.

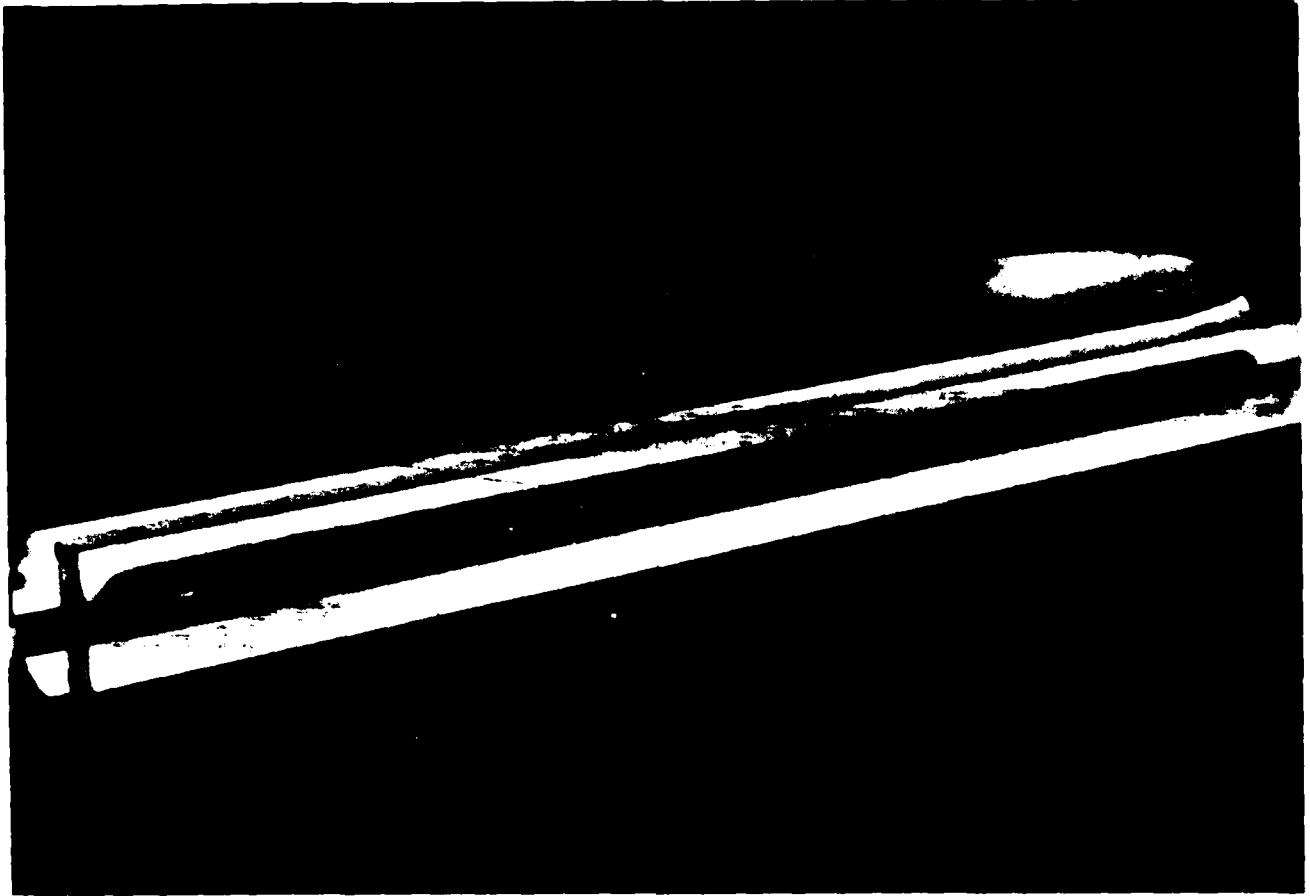


FIGURE 5. CRT WITH POLYSTYRENE FACEPLATE AND HOLLOW METALLIC WAVEGUIDE.



FIGURE 6. CLOSE-UP OF WAVEGUIDE AND FACEPLATE ASSEMBLY.

2. $\text{CuCl}_2 \cdot 2\text{H}_2\text{O}$ (Cupric Chloride-dihydrate)
Vendor: J. T. Baker
Particle Size: 325 mesh
Purity: 99.997 percent
Molecular Weight: 170.47
Density: 2.54
Melting Point: 100 C
3. CdS (Cadmium Sulfide)
Vendor: Cerac Inc.
Particle Size: 325 mesh
Purity: 99.999 percent
Molecular Weight: 144.47
Density: 4.82 (Hex), 4.50 (Cubic)
Melting Point: 1475 ± 15 C (Argon - 10 atmospheres).

Preparation

All of the above materials were ground and screened to 325 mesh in the following mixture ratio:

CdS, 1 mole, 14.45 grams

CdCl_2 (2-1/2 H_2O), 0.3 mole, 6.85 grams

CuCl_2 (2 H_2O), 3.6 milligrams.

(Total batch weight = 21.30 grams.)

The mixture was placed in 400 ml of J. T. Baker xylene and homogenized with an ultrasonic mixing probe for 5 minutes at 300 watts. This mixture was then placed in a ceramic crucible and heated on a hot plate in air at 140 C for 25 minutes to drive-off the xylene.

The residual solids were then re-ground and screened to 325 mesh. This powder was then placed in a ceramic boat and fired (pre-sintered) in a quartz furnace tube in air at atmospheric pressure for 30 minutes at 550 C.

This sintering procedure produces an initial maroon color but subsequent cooling to room temperature produces a greenish brown color. The material is now agglomerated in a solid bar. It is ready for re-grinding and mixing with a solvent for airbrushing.

The material is re-ground to 325 mesh and mixed with xylene. It appears burnt orange in color. An airbrush is used to spray the mixture on the polystyrene faceplate or on glass

microscope slides for a conductivity measurement. After air drying, resistance was measured by a 4-point probe.

In thicknesses of 0.0025 cm, the following properties were observed. (Table I)

TABLE I. CdS LAYER PROPERTIES

	Light (140,000 ft-candles)	Dark
Ohms/square	1.8×10^3	$>20 \times 10^6$
Resistivity, ohm-cm	4.5	$>0.5 \times 10^5$

Photoconductive rise time and decay time were also measured. Results were typically 200 μ second rise time and 10 milliseconds decay time.

4.2.2 Antenna Measurements

Initially, unlike Figure 2, the polystyrene faceplate was constructed to be 3 mm thick at the source end of the waveguide and 1.5 mm thick at the exit end. No interaction with the waveguide was noted when the CRT electron beam was applied with a 2 mm line spacing. The Tektronix 4052 computer control (Figure 7) allowed various line spacings to be commanded, with no observable effect.

After the faceplate was machined to a tapered thickness between 1.5 mm and 0.55 mm, as shown in Figure 2, the observed reaction was a 4 percent reduction in power to the waveguide's matched load and no observed increase or change in reflected power from the antenna. This reaction indicated a radiated power of 4 percent of the waveguide power. Prior to this observation the CRT high voltage and/or filament circuits had failed several times, and before the radiated power angular distribution could be measured, the CRT failed again. The radiation angle was near 70°, but not accurately measured with the 2 mm line spacing on the CdS.

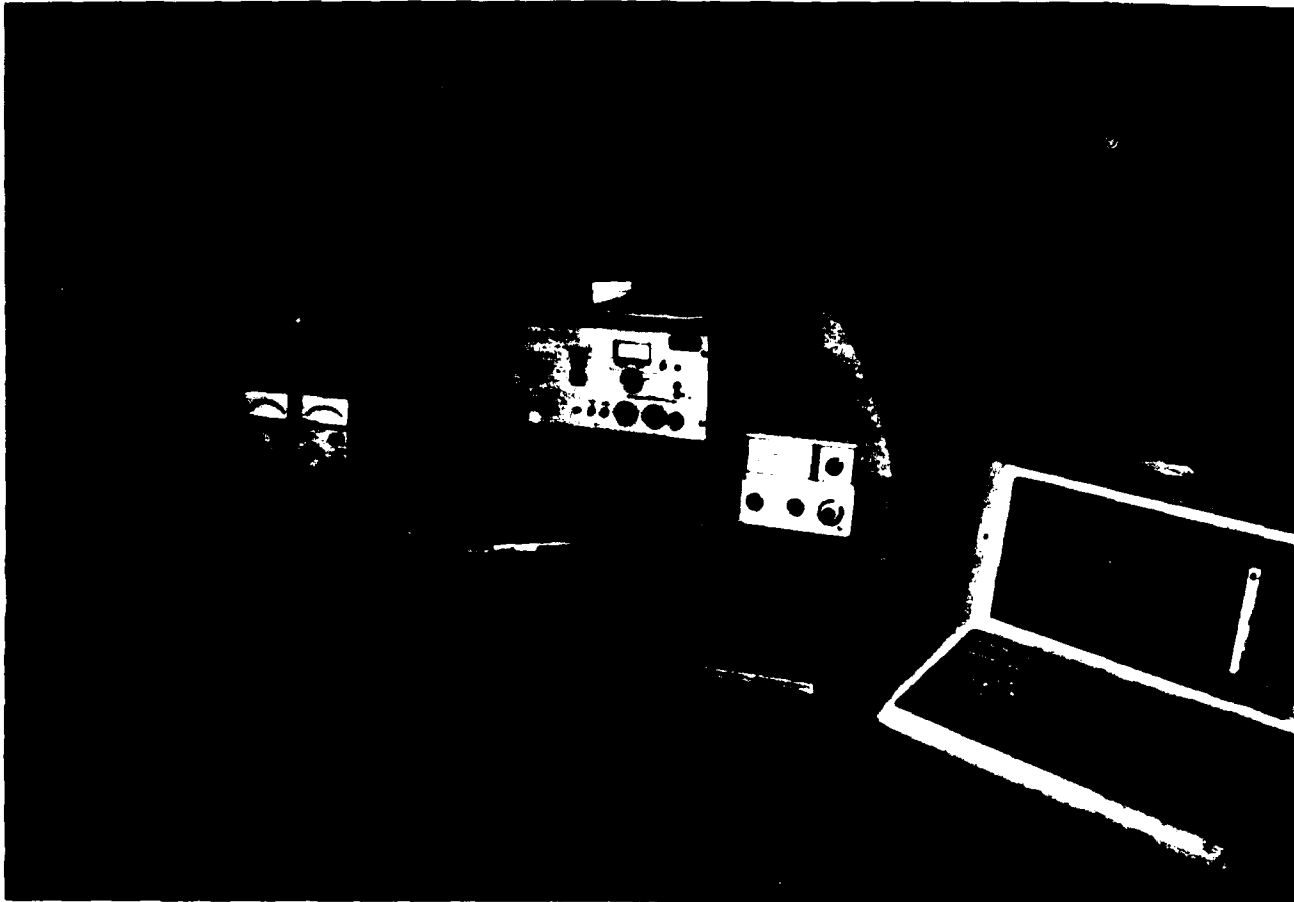


FIGURE 7. OVERALL EXPERIMENTAL ARRANGEMENT WITH CRT REMOVED.

In order that the radiation characteristics of the quartz-polystyrene structure could be known, the quartz waveguide was re-configured over a metallic periodic structure of 2 mm spacing. A polystyrene wedge, 1.5 mm to 0.5 mm, was also used for comparison. The radiation results are shown in Figure 8.

The maximum radiation angle was 78.5° without the polystyrene between the quartz waveguide and the metallic structure. The beam steering equation yields:

$$\begin{aligned}\cos 78.5^\circ &= \frac{c}{v_g} - \frac{\lambda}{\ell} \\ &= \frac{c}{v_g} - \frac{3.2}{2}\end{aligned}$$

Hence

$$\frac{c}{v_g} = \cos 78.5^\circ + 1.6 \approx 1.8$$

for the quartz waveguide. This is consistent with the relative dielectric constant of 3.8 and with the dominant TM waveguide mode.

4.2.3 Potential Improvements

Time and funding did not permit continued optimization of the CRT antenna. Suggested areas for improvement are:

- CdS thickness. Modulation of a greater thickness should prove advantageous. This structure is analogous to the grooved blocks, which show improved performance with a groove depth of about 0.2λ .
- Protective film over the CdS. The tube manufacturer uses a thin copper film over the phosphor to prevent contamination. This film should be employed over the CdS in thicknesses less than a few microns so as to minimize electron beam losses.
- Film resistance. The starting resistance needs to be optimized in conjunction with thickness.
- Separation from waveguide. The 1.5 mm to 0.5 mm spacing needs to be examined. Evanescent coupling might be improved with slightly thinner polystyrene faceplates, but ultimately the thickness limit will be set by the need to sustain vacuum.

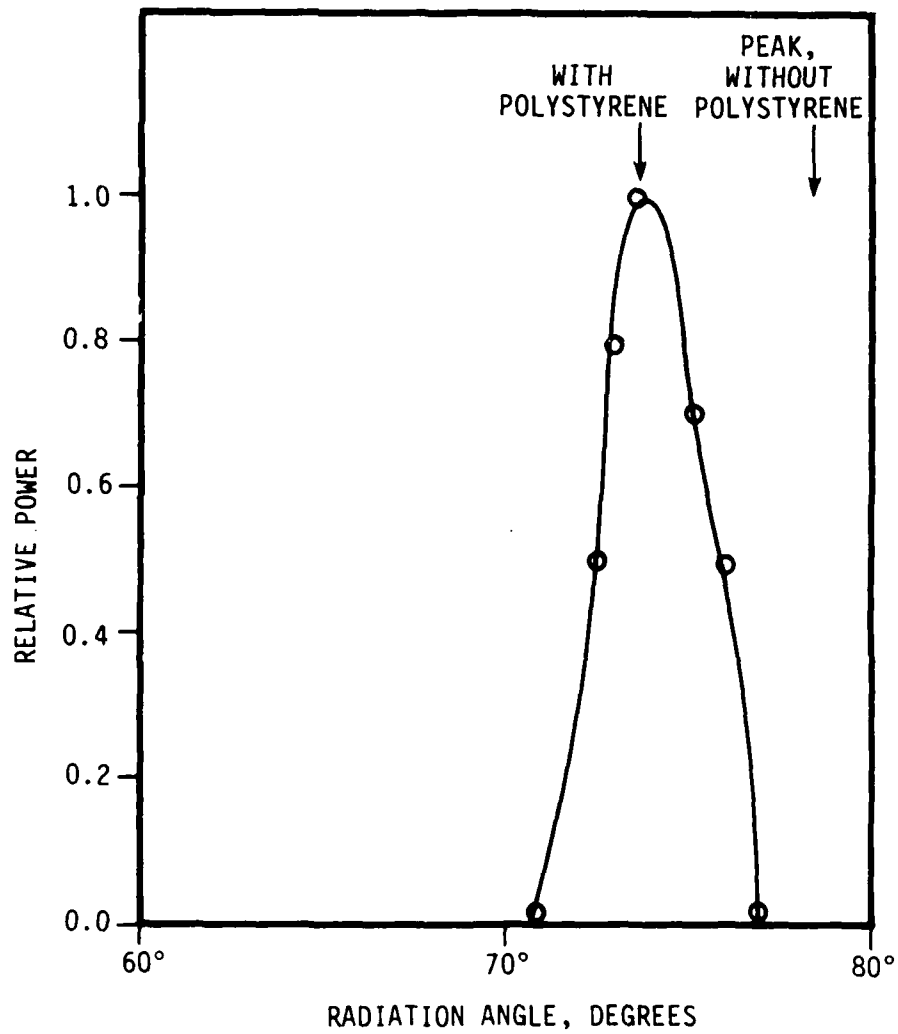


FIGURE 8. RADIATION PATTERN WITH 2 mm SPACING QUARTZ WAVEGUIDE.

5.0 CONCLUSIONS

It is concluded from these studies that photoconductive periodic structures, driven by laser illumination, do not offer a practical solution to beam steering. The required laser illumination levels appear to be excessive and a compact, low cost system would not be obtained.

The cathode-ray-tube drive for diffraction electronics appears promising, but optimized performance has not been demonstrated. If additional experiments could be accomplished toward improved performance, beam steering changes of about 300 positions per second appears feasible.* This optimization would involve film thickness, film resistivity, and protective films to prevent cathode and filament contamination.

*Conventional TV tubes can display 500 lines at 30 frames/sec. If 50 lines are required for the periodic structure, then $500 \times 30/50 = 300$ positions/sec.

6.0 PUBLICATIONS/CONTACTS

Battelle intends to pursue the CRT concept under IR&D funds and eventually publish the results. Contact has been made with the following laboratories who have expressed interest in pursuing the CRT driven antenna for millimeter-wave applications.

U.S. Army, Vulnerability Assessment Laboratory, White Sands,
New Mexico (Code SLCVA-TAC)

U.S. Air Force, Aeronautical Systems Division, WPAFB, Ohio
(Code ENSSS).

7.0 PERSONNEL

The research conducted during the past year has involved the following persons.

Eugene R. Leach: Principal Investigator

Milton R. Seiler: CRT experiments and coordination with previous phases

Dr. Keith Shubert: Tektronix 4052 computer control of the CRT

James A. Robbins: Laser diode experiments

Jennifer I Halman: Photoconductor sensitivity analysis

Brad L. Chapman: Technician responsible for all millimeter-wave measurements, CRT antenna construction, and CdS film preparation.

Records were maintained in Battelle Laboratory Book No. BC-014158.

8.0 REFERENCES

- (1) Seiler, M. R., and Ridgway, R. W., "Studies of Millimeter-Wave Diffraction Devices and Materials", Final Report, Contract No. F49620-82-C-0099, December 1984. 127 pages.
- (2) Seiler, M. R., and Mathena, B. M., "Millimeter-Wave Beam Steering Using Diffraction Electronics", IEEE Trans. Ant. & Prop., Vol. AP-32, No. 9, September 1984, pp 987-990.
- (3) Afsar, M. N., and Button, K. J., "Precise Millimeter-Wave Measurements of Complex Refractive Index, Complex Dielectric Permittivity and Loss Tangent of GaAs, Si, SiO₂, Al₂O₃, BeO, Macor and Glass", IEEE Trans. Microwave Theory & Techniques, Vol. MTT-31, No. 2, February 1983, pp 217-223.

APPENDIX

PHOTOCONDUCTOR STUDIES

Efforts were also directed toward laser illumination of amorphous Si, CdS, and GaAs films. The results were unsuccessful as far as implementing a diffraction antenna by these methods. A critical limiting factor is the fact that the laser illumination can only modulate a few microns of the photoconductor layer. The CRT concept, on the other hand, potentially offers greater modulation depth. These topics are discussed and documented below.

Previously, laboratory experiments were conducted with a laser-excited photoconductor to achieve a periodic structure. In those experiments, a 1.06 micrometer Nd:YAG Quantel laser which creates 10 pulses per second, each approximately 300 picoseconds to 3 nanoseconds wide, was used. The beam from this laser was "spoiled" so as to fill a reflecting mirror that was 2.5 inches in diameter. The beam was then passed through a 400 mm focal length cylindrical lens so that a rectangular area 6 mm by 63 mm was illuminated near a polystyrene waveguide. An amorphous silicon film coated on a fused silica microscope slide was placed within the evanescent mode coupling distance from the waveguide. Using a laser illumination of approximately 0.65 mJ/cm^2 at a pulse repetition frequency of 10 Hz, a spatial conductivity variation on the silicon film was created, resulting in steering of the 94 GHz beam at an angle of 76 degrees.

As a result of the previous studies, it was determined that a film is desired which permits control of dark resistivity and thickness and yet optimizes photoconductive response. The initial efforts of the current program were to be directed towards using frequency doubled Nd:YAG laser radiation to optimize the use of amorphous and single crystal materials for 94 GHz beam steering. A logical starting place for these optimization efforts involved a reproduction of beam steering measurements made during the previous AFOSR-supported millimeter-wave diffraction program. Unfortunately, the experimental study effort was severely hampered by repeated failures of the Quantel laser with a more-than-desired effort made to return the laser to a useful operational status. Continued instabilities in the die cell due to aging, the strong sensitivity of beam alignment on

internal system optical components, continued problems with the avalanche transistors in the pulse slicer, and failure of the pulse power supply led us to eventually abandon the possible use of the Quantel laser for any additional beam-steering experiments.

The experimental effort was subsequently directed towards an evaluation of the use of an array of laser diodes to irradiate the materials for evaluation of their performance related to 94 GHz beam steering. An array of five (5) M/A Com LD-60 series pulsed laser diodes and power supplies were assembled for these experiments. These laser diodes had an average output of 3.0 Watts at 1.06 micrometers and were operated at a 10 kHz repetition rate. The five laser beams were focused onto a glass microscope slide that had been coated with 1 μm of amorphous silicon. The slide was suspended under a polystyrene waveguide with a spacing of 1 mm on the power feed, and 0.5 mm on the load end of the guide. A reflex klystron with a power output of 300 mW at 94 GHz was used as the microwave source. The load and beam power were monitored by suspending one of the thermistor mounts, fitted with a Boystron #7R.67/25 feed horn, over the polystyrene waveguide on a 36" radius, graduated dielectric arch. Several waveguide-to-photoconductor spacings and laser power levels were effected with no discernible power decoupling being observed at the load thermistor.

To better understand these negative results, an analytical evaluation of the photoconductive properties of amorphous silicon (a-Si) was made. The photoconductive properties of amorphous silicon were found to be very sensitive to the method used to prepare the amorphous silicon. The common methods of preparation are:

- 1) sputtering
- 2) vacuum evaporation
- 3) rf or dc glow discharge from silane or disilane gas

By changing the substrate temperature during deposition, the ambient temperature during deposition, or the hydrogen content of the a-Si, the dark conductivity and photoconductivity of the a-Si can be increased, but it does not appear that the dark conductivity can be increased to the desired value of greater than $0.01 \text{ ohm m}^{-1} \text{ cm}^{-1}$.

Amorphous silicon made by evaporation or sputtering generally has a higher dark conductivity than glow discharged amorphous silicon. Sputtered a-Si specimens have a dark conductivity of 10^{-10} - $10^{-4} \text{ ohm}^{-1} \text{ cm}^{-1}$ (A-1). The

dark conductivity of rf glow discharged hydrogenated amorphous silicon (a-Si:H) from silane is 10^{-11} - 10^{-7} ohm $^{-1}$ cm $^{-1}$ (A-2). However, if the glow discharged a-Si:H is doped with PH $_3$ or B $_2$ H $_6$, the dark conductivity can be increased to up to 10^{-2} ohm $^{-1}$ cm $^{-1}$ (A-3), depending on the amount of doping and the substrate temperature during deposition.

The photoconductivity of a material depends on the density of states in the bandgap. Evaporated and sputtered specimens have a large density of states in the bandgap, resulting in extremely short carrier lifetimes and low photoconductivity. The presence of hydrogen in amorphous silicon decreases the density of states. Pure a-Si has a density of states of greater than 10^{20} cm $^{-3}$ eV $^{-1}$ and a-Si:H has a density of states of 10^{17} cm $^{-3}$ eV $^{-1}$ (A-4). The lower density of states in the bandgap in a-Si:H allows longer carrier lifetimes and higher photoconductivity in a-Si:H. The carrier lifetime of glow discharged a-Si:H is 10^{-4} - 10^{-6} s (A-5). A substrate temperature of 550K results in the highest photoconductivity for glow discharged a-Si:H (A-6).

In general, the photoconductivity of a specimen can be expressed as:

$$\sigma_p = K n_n u_n t_n$$

where

$$K = q N_0 (1-R) (1-e^{-ad}) / L$$

n_n = generation efficiency of free carriers

u_n = electron mobility

t_n = electron lifetime

a = optical absorption coefficient

N_0 = photon flux

R = surface reflectivity

d = film thickness

L = appropriate drift distance

q = electron charge

The quantity K depends only on the incident photon flux that is absorbed in the film. The optical absorption coefficient of a-Si:H is approximately 5×10^3 - 5×10^5 cm $^{-1}$, (10^3 cm $^{-1}$ at 1.3 eV) (A-7). The optical absorption coefficient is greatest when the incident photon energy is greater than the optical bandgap energy E_g . The optical energy bandgap of glow discharge a-Si:H is estimated to be 1.55 eV (A-8). If the incident

radiation is at $.904 \mu\text{m}$, the photon energy is only 1.3 eV and the incident photon energy is below the bandgap energy. The electron mobility has been estimated at from less than $.04$ to $10 \text{ cm}^2/\text{Vs}$ (A-9,A-10,A-11) for glow discharged amorphous silicon, depending on the temperature of the substrate at the time of deposition. By contrast, the electron mobility of crystalline silicon is $10^3 \text{ cm}^2/(\text{Vs})$ (A-12) and the absorption coefficient is $5 \times 10^2 - 5 \times 10^4 \text{ cm}^{-1}$, depending on the incident photon energy (A-13).

The energy flux required to obtain a photoconductivity of 1000 times the dark conductivity, where the dark conductivity is greater than $10 \text{ ohm}^{-1}\text{cm}^{-1}$, can be estimated in the following manner. Assuming that a dark conductivity of $10^{-2} \text{ ohm}^{-1}\text{cm}^{-1}$ could be obtained by doping glow discharged a-Si:H, a photoconductivity of $10 \text{ ohm}^{-1}\text{cm}^{-1}$ would be needed. If $ad \ll 1$, the photoconductivity is

$$\sigma_p = q N_0 (1-R) a d n_n t_n u_n / L .$$

If $d=L$,

$$\sigma_p = q N_0 (1-R) a n_n t_n u_n .$$

Under the most favorable conditions,

$$R = 0$$

$$a = 10^4 \text{ cm}^{-1}$$

$$u_n = 10 \text{ cm}^2/(\text{V s})$$

$$t_n = 10^{-5} \text{ s}$$

$$n_n = 1 .$$

Then, if the photoconductivity is to be $10 \text{ ohm}^{-1}\text{cm}^{-1}$, then the incident energy flux required is $P = 13.75 \text{ watts/cm}^2$ for radiation at $.904 \mu\text{m}$. This power is much too high to be practical. From this calculation, it appears that a photoconductivity of $10 \text{ ohms}^{-1}\text{cm}^{-1}$ is not easily obtained in amorphous silicon. An a-Si-F-H alloy made by rf glow discharge in SiF_4 and H_2 and doped with PH_3 and AsH_3 reportedly has a dark conductivity of $5 \text{ ohm}^{-1}\text{cm}^{-1}$ and energy bandgap of E_g of 1.65 eV (A-14), but for an incident energy flux of 90 mW/cm^2 , the photoconductivity is only $10^{-4} \text{ ohm}^{-1}\text{cm}^{-1}$.

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